Heavy-Duty Vehicle In-Use NOx Testing Project

Interim Report

NESCAUM

Environment and
Climate Change Canada

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Changement climatique Canada

Acknowledgements

Introduction

This paper provides the results from real-world Class 8 truck activity and emissions data gathering conducted in the Northeast and Mid-Atlantic states. There is little available data on in-use operation and emissions performance from heavy-duty trucks in this region. The purpose of the study is to add to the literature on real-world truck operation and emissions in the Northeast and mid-Atlantic; to analyze the emissions data using recently established methods; and to assist air quality regulators in identifying priorities for new heavy-duty engine and vehicle emission standards and test procedures. The Northeast States for Coordinated Air Use Management (NESCAUM) conducted this project jointly with Environment and Climate Change Canada (ECCC). Given the proximity of the truck routes evaluated in this project to the eastern Canadian provinces, the information is of interest to ECCC as well.

Background

Heavy-duty vehicles contribute approximately 20 percent of total oxides of nitrogen (NOx) emissions in the Northeast and mid-Atlantic states.[1] NOx emissions are a primary precursor to the formation of ground-level ozone and secondary fine particulate matter ($PM_{2.5}$) and contribute to acid deposition, eutrophication, and visibility impairment. NOx emissions are the major drivers of surface ozone concentrations at the regional scale in the eastern United States. Epidemiological studies provide strong evidence that ozone is associated with respiratory effects, including increased asthma attacks, as well as increased hospital admissions and emergency department visits for people suffering from respiratory diseases. Ozone can cause chronic obstructive pulmonary disease (COPD), and long-term exposure may result in permanent lung damage, such as abnormal lung development in children. There is also consistent evidence that short-term exposure to ozone increases risk of death from respiratory causes.[2] Furthermore, recent studies show that ozone concentrations below the current National Ambient Air Quality Standards (NAAQS) continue to contribute to the risk of premature death in sensitive populations, such as the elderly.[3]

According to the Manufacturers of Emission Controls Association, since the introduction of the federal 2007/2010 heavy-duty engine NOx emissions standards, there have been significant technology advances that provide a foundation for reducing NOx emissions a further 90 percent.[4] To do this, manufacturers will need to introduce hardware upgrades and new aftertreatment systems that, while significant, build upon the architecture of current emissions control systems. Note that the current U.S.

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[1] U.S. EPA 2017 National Emissions Inventory.

[2] U.S. EPA, "Health Effects of Ozone Pollution," Available at https://www.epa.gov/ground-level-ozone-pollution/health-effectsozone-pollution.

[3] Di, Q., et al. "Air pollution and mortality in the Medicare population." New England Journal of Medicine 376: 2513-2522 (2017). DOI: 10.1056/NEJMoa1702747; Di, Q., et al. "Association of short-term exposure to air pollution with mortality in older adults." JAMA 318: 2446-2456 (2017). DOI: 10.1001/jama.2017.17923.

[4] MECA, "Technology Feasibility for Heavy-Duty Diesel Trucks in Achieving 90% Lower NOx Standards in 2027," February 2020. Available at http://www.meca.org/resources/MECA_2027_Low_NOx_White_Paper_FINAL.pdf

federal emission standards are in the process of being updated and changes to the current federal in-use test for heavy-duty trucks, called the "not-to-exceed" (NTE) protocol are being considered.[5]

According to the International Council on Clean Transportation (ICCT), the NTE test excludes a significant portion of in-use emissions.[6] Emissions that occur during low load operation are of particular concern. The NTE excludes emissions when trucks are operating at low loads, defined as below 30 percent of maximum engine torque and power, as well as emissions occurring during other so-called "carve-out" conditions. A recent ICCT analysis of NTE data submitted by manufacturers found that approximately 40 percent of total truck NOx emissions were emitted at low load conditions.[6]

A new, more rigorous in-use test protocol has been proposed by the California Air Resources Board (ARB) and is in the process of being finalized in ARB's "Low NOx Omnibus Regulation". [7] The regulation establishes a moving average window (MAW) approach to segmenting and quantifying NOx emissions at different in-use load conditions. The MAW procedure and the accompanying proposed emissions standards for idle and low load operation aim to significantly reduce truck NOx emissions at low load and idle, and, more broadly, for the operating conditions excluded by the NTE protocol. The ARB MAW approach has been used in this analysis to illustrate the fraction of NOx emissions that could be reduced with its introduction, and to illustrate how the method can be applied to in-use test data.

Methods

This section provides an overview of the method used in this study. The approach had four components:

1) Select a trucking fleet to participate in the study and identify trucks for data logging;
2) Equip Class 8 tractors with data loggers and collect data over periods of warm and cold weather;
3) Analyze the data for activity and emissions; and
4) Bin the data and obtain the results according to the ARB MAW method described in the Omnibus Initial Statement of Reasons (ISOR).[7]

Fleet and Truck Selection

NESCAUM worked with U.S. EPA Region 1, the Northeast Diesel Collaborative, and others to identify a fleet in the Northeast to participate in the data gathering project and Regency Transportation was

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[5] U.S. EPA issued an Advance Notice of Proposed Rulemaking on the Cleaner Trucks Initiative in January 2020. For more information on the ruelmaking see: https://www.epa.gov/regulations-emissions-vehicles-and-engines/cleaner-trucks-initiative.

[6] Badshah, H., Posada, F., Muncrief, R., "Current State of NOx Emissions from In-Use Heavy-Duty Diesel Vehicles in the United States," November 2019.

[7] California Air Resources Board, "PUBLIC HEARING TO CONSIDER THE PROPOSED HEAVY-DUTY ENGINE AND VEHICLE OMNIBUS REGULATION AND ASSOCIATED AMENDMENTS: Proposed Amendments to the Exhaust Emissions Standards and Test Procedures for 2024 and Subsequent Model Year Heavy-Duty Engines and Vehicles, Heavy-Duty On-Board Diagnostic System Requirements, Heavy-Duty In-Use Testing Program, Emissions Warranty Period and Useful Life Requirements, Emissions Warranty Information and Reporting Requirements, and Corrective Action Procedures, In-Use Emissions Data Reporting Requirements, and Phase 2 Heavy-Duty Greenhouse Gas Regulations, and Powertrain Test Procedures STAFF REPORT: INITIAL STATEMENT OF REASONS," DATE OF RELEASE: June 23, 2020 , see https://ww3.arb.ca.gov/regact/2020/hdomnibuslownox/isor.pdf.

selected. The company operates a fleet of 150 Class 8 day cabs and sleeper cabs that operate on a variety of routes, some confined to the Northeast and mid-Atlantic and some that are cross-country. The Regency trucks haul a range of freight including beverages, office supplies, home goods, and other products. The trucks operate in northern states in the winter, which was desirable given the opportunity to collect data in cold ambient temperatures. Trucks were selected for this project based on their routes – trucks that return to Regency's Franklin, Massachusetts facility were selected to ensure that data loggers could be collected from the trucks after a month or more of data logging was completed.

NESCAUM equipped five Freightliner Class 8 trucks with data loggers. Three of the five trucks selected were sleeper cabs and two were day cabs. One truck traveled almost exclusively in the State of Maine and others traversed the Northeast region. Table 1 provides information on the participating trucks.

Table 1: Test Truck Information

Truck Make	Model	Model Year	Configuration	Engine Model	Engine Manufacturer	Truck Number
Freightliner	CA126SLP	2018	Sleeper cab	DD15	Detroit Diesel	490
Freightliner	CA126SLP	2019	Sleeper cab	DD15	Detroit Diesel	530
Freightliner	CA116DC	2020	Day cab	DD13	Detroit Diesel	565
Freightliner	CA126SLP	2020	Sleeper cab	DD15	Detroit Diesel	568
Freightliner	CA116DC	2020	Day cab	DD13	Detroit Diesel	583

Data Collection

The U.S. EPA loaned some HEM™ data loggers to NESCAUM for use in the project. NESCAUM installed files on the data loggers that defined data sampling frequency, conditions for data collection (e.g. only when the vehicle engine is on), broadcast signals to collect, and other parameters. DawnEdit2 software was used to install software on the data loggers and to make adjustments to files. Once the data loggers were configured for the Freightliner trucks, NESCAUM installed the data loggers on the OBD ports in the truck cabs.

Figure 1 shows the placement of a data logger in a Freightliner tractor. The data loggers were fitted with labels indicating the loggers were the property of U.S. EPA and that drivers should not remove them. The data logging began in February of 2020 and continued through the summer of 2020. Data loggers remained in place for three to six weeks, depending on the truck routes. Data loggers were removed when the trucks returned to the Franklin, Massachusetts Regency Transportation facility. The number of days of data logging for each truck varied, in part because of the Covid-19 pandemic and in part related to the truck routes. Table 2 shows the number of shifts captured for each truck, the date of installation, and date of removal. Some shifts spanned more than one day.

Figure 1: Data Logger Placement

Table 2: Number of Shifts of Data Logging for Each Truck

Truck No.	Number of Shifts Data Logged	Date Data Logger Installed	Date Data Logger Removed
490	16	5/15/2020	6/13/2020
530	15	2/13/2020	3/10/2020
565	28	7/12/2020	8/14/2020
568	25	7/22/2020	9/1/2020
583	17	2/4/2020	2/27/2020

The software files installed on the data loggers collected data from each truck's engine control modules for over 150 parameters. A sample of the types of data collected is provided in Table 3. A full list of data collected is provided in Appendix A.

Table 3: Example Parameters Measured from the Truck Engine Control Modules

Engine Parameters	Engine Speed (RPM)
	Engine fuel mass flow rate (g/s)
	Engine torque (Nm)
Aftertreatment Parameters	Diesel Exhaust Fluid (DEF) dosing rate
	Exhaust temperatures pre and post SCR catalyst
	NOx sensor active status
	Exhaust mass flow rate
Vehicle Parameters	Vehicle speed (via wheel rotation)
	Transmission gear selected
Other	Ambient temperature
	Global Positioning System (GPS) location and speed

Data was gathered at a rate of 1 Hz for each parameter shown in Table 3 and Appendix A. A total of 101 shifts of data from the five trucks were gathered as part of the project.

Data Analysis

The raw logger data was converted to CSV format using DawnEdit2 software and was imported into RStudio for additional processing. Using the recorded timestamp, the data was collected into "test days." These test days include a cold start and a full shift of driving operation, including breaks and loading/unloading time when the vehicle was turned off.

For vehicle speed, the J1939 vehicle speed signal was used instead of the GPS as it was deemed more reliable. Using these available sources of data, a time-speed trace for the test days was determined.

Fuel consumption rates were used to determine the window normalized average carbon dioxide (CO_2) emission rate. This CO_2 emission rate was then used to apply the binning rules as specified by ARB. NO_x emissions broadcast from the engine control module as parts per million were converted to mass emissions rates using the broadcast exhaust gas flow rate. Due to the limitations of on-board NO_x sensors, these sensors were not active a portion of the time and so did not report any NO_x emissions during start-up and low exhaust temperature conditions. Representative data was added to account for

this time prior to calculating the sum-over-sum emissions rates in each bin. This is described in more detail in the Additional Calculations and Assumptions section.

Moving Average Window

ARB has approved an amendment that replaces the current NTE-based methodology with a new moving average window "MAW" methodology for 2024 and subsequent model year engines.[8] For this analysis, we used the procedure for 2024 to 2026 engines which has a cold start and low power exclusion. For diesel engines, three bins related to the applicable standards are used to determine compliance. The three diesel-cycle MAW-based bins represent idle, low load, and medium/high load operations based on their normalized carbon dioxide emission rates, which is used as a proxy for engine load.[9] Compliance is determined by comparing the sum-over-sum NOx emissions for each bin to the in-use threshold, defined as one and a half times the applicable NOx standard for the model year (MY).

In order to apply the proposed binning and MAW calculations to the data set, the normalized CO_2 emissions rate based on the raw CO_2 emissions rate and the Family Certification Limit (FCL) is required[10]. The J1939 data includes the fuel consumption rate, and this was combined with estimated fuel specifications to determine an approximate CO_2 mass emissions rate.

$$\dot{m}_{CO2} = \dot{m}_{fuel} * FFC * \frac{M_{CO2}}{M_C}$$

Where:

- $\dot{m}_{CO2}$ is the mass emission rate of CO_2 in g/s
- $\dot{m}_{fuel}$ is the mass flow rate of fuel in g/s
- FFC is the fuel fraction carbon (estimated based on typical diesel fuel composition – 0.87 was used)
- M_{CO2} is the molar mass of CO_2 (44.0095 g/mol)
- M_C is the molar mass of carbon (12.0111 g/mol)

Using this calculated mass emissions rate of CO_2 and the FCL limit for the engine model in grams per brake horsepower hour (g/bhp-hr), the window normalized CO_2 emissions rate was calculated using the ARB procedure as follows:

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[8] California Air Resources Board Resolution, Heavy-Duty Engine and Vehicle Omnibus Regulation and Associated Amendments, "Proposed Amendments to the Exhaust Emissions Standards and Test Procedures for 2024 and Subsequent Model Year Heavy-Duty Engines and Vehicles, Heavy-Duty On-Board Diagnostic System Requirements, Heavy-Duty In-Use Testing Program, Emissions Warranty Period and Useful Life Requirements, Emissions Warranty Information and Reporting Requirements, and Corrective Action Procedures, In-Use Emissions Data Reporting Requirements, and Phase 2 Heavy-Duty Greenhouse Gas Regulations, and Powertrain Test Procedures Resolution 20-23, August 27, 2020, see Resolution 20-23 Low NOx Omnibus Amendments (ca.gov).
[9] For Otto cycle engines, a single bin encompassing all operations is used. This is not relevant for this study because we have only gathered data from diesel engines.
[10] CO_2 FCLs serve as the CO_2 emission standards for the engine family with respect to certification and confirmatory testing.

$$window\ normalized\ average\ CO_2\ rate = \frac{\left(\sum_{t=1}^{n} \dot{m}_{CO2}(t)\right)}{FCL * \left(P_{max} * \frac{n}{3600}\right)}$$

Where:

- window normalized average CO_2 rate is a value between 0 and 1 (corresponding to 0-100% load)
- $\dot{m}_{CO2}$ is the mass emission rate of CO_2 in g/s
- FCL is the family certification limit of the engine in g/bhp-hr
- P_{max} is the maximum rated power of the engine in bhp
- n is the window length in seconds (300 s for this procedure)

Binning Procedure

Based on the window normalized average CO_2 rate, the test data was split into three bins: idle, low load, and med/high load. These bins correspond to different operating modes for the vehicle and have separate proposed NO_x emissions limits. The test data was classified based on the window normalized average CO_2 emissions rate with the following values:

$$\begin{cases} norm_{CO2} \leq 6\% \rightarrow idle\ bin \\ 6\% < norm_{CO2} \leq 20\% \rightarrow low\ load\ bin \\ 20\% < norm_{CO2} \rightarrow med/high\ load\ bin \end{cases}$$

NOx Emissions Conversion from Concentration to Mass Rate

The raw tailpipe NO_x concentrations were converted to mass emission rates using the following formula:

$$\dot{m}_{NOx} = \frac{Conc_{NOx}}{10^6} * \dot{m}_{exh} * \frac{M_{NOx}}{M_{exh}}$$

Where:

- $\dot{m}_{NOx}$ is the mass emission rate of NO_x in g/s
- $Conc_{NOx}$ is the reported concentration of NO_x from the on-board sensor
- $\dot{m}_{exh}$ is the mass emission rate of exhaust gas in g/s as reported by the on-board computer
- M_{NOx} is the molar mass of NO_x (46.01 g/mol, est.)
- M_{exh} is the molar mass of exhaust gas (28.965 g/mol, est.)

Sum-Over-Sum Emissions Calculations

The protocol described by ARB uses the sum-over-sum emissions when comparing binned emissions to regulated limits. Calculating the sum-over-sum emissions of NO_x varies between bins, with bin 1 having a separate calculation method to obtain values in g/hr while bins 2 and 3 report values in g/bhp-hr. The equations used are as follows:

$$e_{sos\ NOx,idle} = \frac{\sum_{k=1}^{n} \dot{m}_{NOx} * \Delta t}{\sum_{k=1}^{n} \Delta t} * \frac{3600\ s}{1\ hr}$$

$$e_{sos\ NOx,bin2/3} = \frac{\sum_{k=1}^{n} \dot{m}_{NOx} * \Delta t}{\sum_{k=1}^{n} \dot{m}_{CO} * \Delta t} * e_{CO\ ,FTP,FCL}$$

Where:

- $e_{sos\ NOx,idle}$ is the sum-over-sum NO_x emissions for the idle bin
- $\dot{m}_{NOx}$ is the moving average window-based mass emission rate of NO_x in g/s
- Δt is the time step (1 s)
- n is the length of the bin in seconds
- $e_{sos\ NOx,bin2/3}$ is the sum-over-sum NO_x emissions for either bin 2 or bin 3 (same equation used)
- $\dot{m}_{CO2}$ is the moving average window-based mass emissions rate of CO_2 in g/s
- $e_{CO2,FTP,FCL}$ is the engine family FTP FCL work-specific CO_2 rate in g CO_2/bhp-hr

Additional Calculations and Assumptions

By using the on-board NO_x sensors to measure NO_x emissions, the HEM logger is able to provide emissions data for weeks (or months) at a time without intervention. However, on-board NOx sensors may be inactive at low loads or when exhaust temperatures drop below (approximately) 190 degrees Centigrade. Some NO_x data at low loads was available when, for example, a truck went from high load operation to moderate or low load operation and the conditions were still favourable for sensor operation. The NO_x sensors were operational approximately 33 percent of the time in bin 1, 69 percent of the time in bin 2, and 89 percent of the time in bin 3.

To supplement NO_x data for bin 2, NESCAUM and ECCC relied on NO_x data gathered during testing conducted by Southwest Research Institute.[11] To supplement bin 1 data, NESCAUM used the idle standard for California certified trucks (all of the participating Freightliner trucks are certified to California's emissions standards). Prior to the sum-over-sum calculations, any missing NO_x mass emissions rates were substituted using the relevant estimates. During the time that the sensor was unavailable, the idle NOx emissions were assumed to be 30 grams per hour, low load NOx emissions were assumed to be 1.0 g/bhp-hr, while the average medium/high load bin value for the rest of the test was used for the medium/high load bin.

Results

Ambient Temperatures

The five trucks operated with data loggers for nine months during 2020. The range of ambient temperatures during the test days is shown in Figure 2. Each dot represents the average temperature

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[11] Sharp, C., "Update on Heavy-Duty Low NOx Demonstration Programs at SwRI,"Southwest Research Institute, September 26, 2019, accessed at
https://ww2.arb.ca.gov/sites/default/files/classic//msprog/hdlownox/files/workgroup_20190926/guest/swri_hd_low_nox_demo_programs.pdf?_ga=2.61143086.34960453.1617199922-1678718972.1597669978.

during one shift of data logging for each truck, with the top whisker representing the maximum temperature during the shift and the bottom representing the minimum. As shown, the five trucks operated in ambient temperatures ranging from -18 degrees Centigrade (0 Fahrenheit) to 43 degrees Centigrade (109 Fahrenheit), spanning the full range of winter, summer, fall, and spring temperatures typical of the Northeast and mid-Atlantic states. The very high temperature of 109 degrees Fahrenheit may be due to the fact that localized temperatures on roadways can exceed surrounding ambient areas due to the roadway surface radiating additional heat.
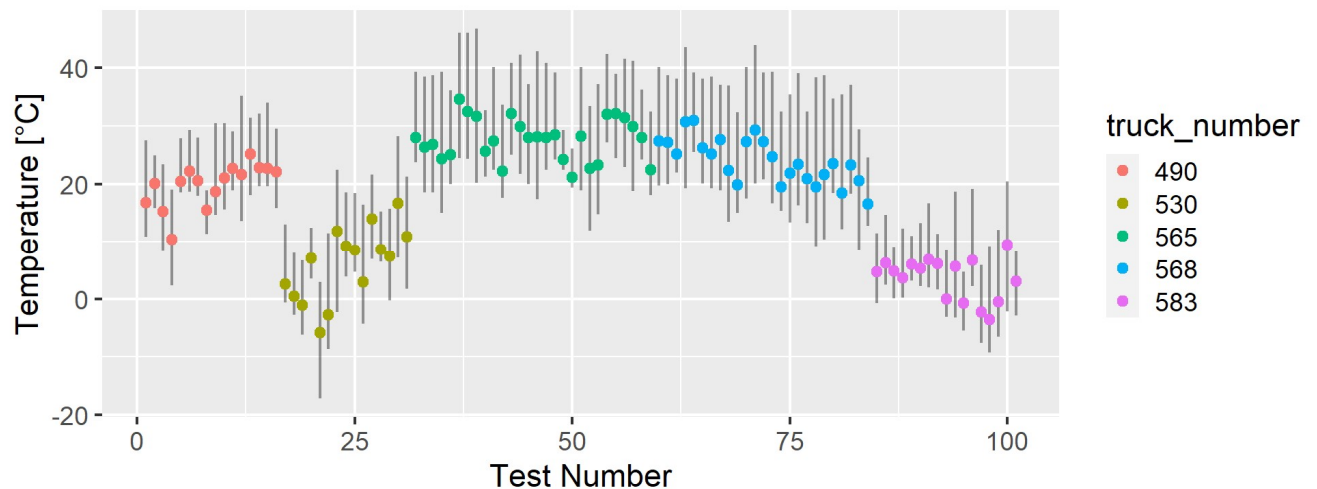

Figure 2: Range of Ambient Temperatures during Each Day of Data Logging

Trucks 583 and 530 operated in the coldest ambient temperatures, while trucks 565 and 568 operated in the warmest ambient temperatures. Trucks 565 and 568 were driven from western New York to North Carolina and back during May and June, while truck 583 was operated almost exclusively in Maine during the winter.

Vehicle Miles Traveled (VMT) and Vehicle Speeds

Figure 3 shows the variation in truck VMT over the 101 shifts of data logging. Some trucks, such as number 490, saw very little variation in daily VMT. Truck 490 was driven between 450 and 500 miles per day nearly all of the 16 days of observed driving. Trucks 530 and 565 had the greatest overall variation in miles traveled per day. Truck 565 was driven between 200 and 600 miles per day, with the median being just under 500 miles per day. Truck 530 traveled between 150 and 490 miles per day with a median of 332 miles per day. Truck 568 traveled a median of 549 miles per day but had days where between 100 and 700 miles were traveled. Lastly, truck 583 traveled a median of 214 miles per day with a low of 50 miles and the highest single day of travel at 950 miles. This 950-mile trip was a double shift over 24 hours and was achieved with separate drivers.
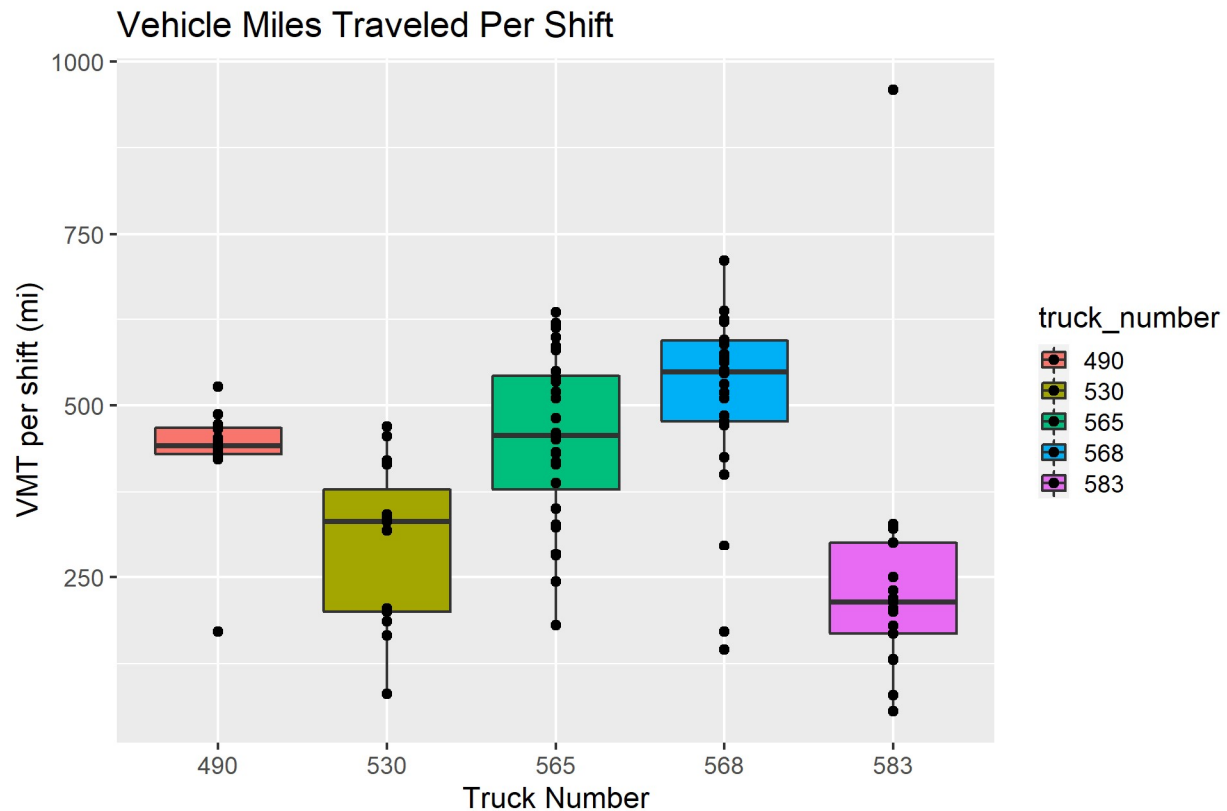
Figure 3: Vehicle Miles Traveled for Each Shift and Truck

Regency reported that in general, its day cabs are driven more miles per year than their sleeper cabs. The reason for this is a new day cab driver often takes over at the end of a shift, allowing the truck to continue on its route. The day cabs shown in Figure 3 are truck 583 and truck 565. Truck 565's VMT is one of the higher values in the test. However, truck 583 had, on average, the lowest VMT. This truck was data logged at the beginning of the Covid-19 shutdown so this may have affected its VMT.

The median VMT for trucks 530 and 583 are well below 500 miles (as shown by the black horizontal line in the figure), while trucks 490 and 565 approached 500 miles, and only 568 had a median VMT over 500 miles. There were generally half-hour or longer breaks within each shift. While tractors are considered a worst-case application for zero emission vehicles such as battery electric trucks, the duty cycle observed in this study is within the range of what could be supported with appropriate fast-charging or fueling infrastructure for battery electric or hydrogen fuel-cell based zero emission vehicles.

The median average daily speed for the trucks ranged from 44 miles per hour (mph) to 58 mph. However, there was a range of individual daily average speeds. Figure 4 shows the percent of time each truck spent at different speeds. Trucks 490 and 565 spent the greatest amount of time at highway speeds (> 60mph). Truck 583 spent the lowest amount of time at highway speed. As was noted earlier, truck 583 travelled almost exclusively in Maine and during the winter months. The other trucks travelled across the Northeastern United States.
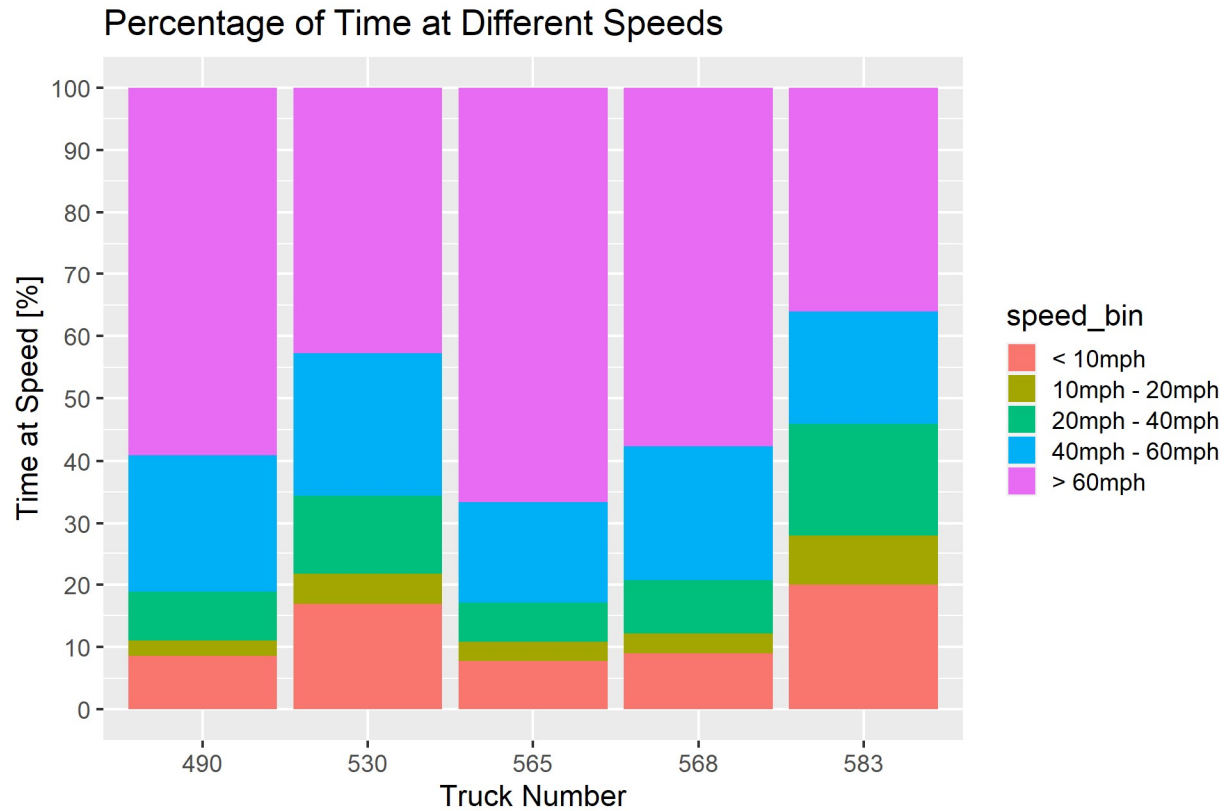
Figure 4: Time Spent at Different Vehicle Speeds

Figure 5 shows the spread of average daily speeds for each truck. Trucks 490, 565, and 568 generally had average daily driving speeds between 50 and 60 miles per hour. This corresponds to the routes each truck operated on with consistent highway driving. Trucks 530 and 583 had greater variability in average daily vehicle speeds.
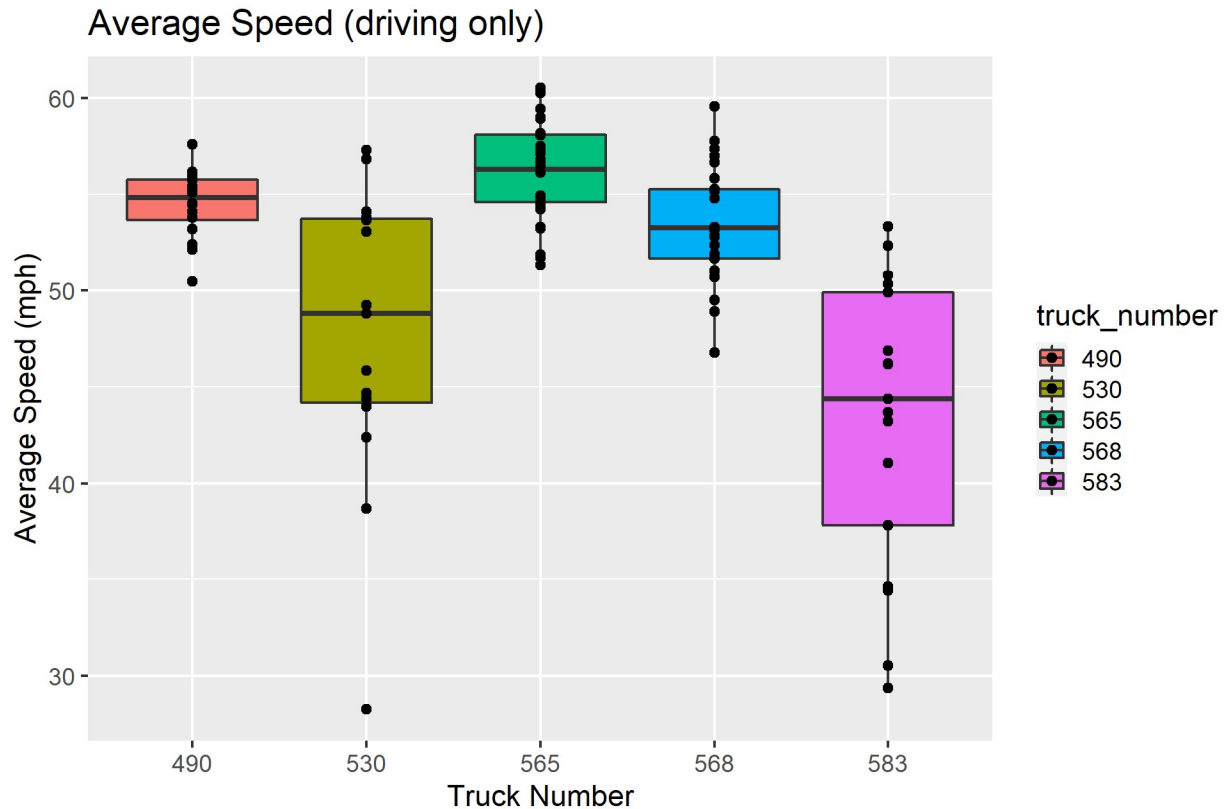
Figure 5: Range of Shift Average Driving Speeds for Each Truck

The average driving speed (excluding idle time) in Figure 5 shows similar trends to the VMT: Vehicles traveling faster went further, assuming a similar shift time. We see that truck 583 traveled both shorter distances and at lower average speeds than the others. Trucks 490, 565, and 568 appear to have spent significant time on expressways, while truck 530 had more variation in driving conditions. Trucks 530 and 583 were tested in winter conditions, and thus lower speeds may be partially attributable to poorer driving conditions.

Binned Operation

The daily shifts for each truck were analyzed to determine how much time was spent at idle (bin 1), low load (bin 2), and medium/high load (bin 3) operation using the three-bin method finalized in the ARB Omnibus regulation. Figure 6 provides a summary of the time each truck spent in each of the three bins. The total number of seconds spent at idle, low load, and high load during data logging were counted and these numbers were divided by the total number of seconds the ignition was turned on for each truck to determine the percent of time in each bin.
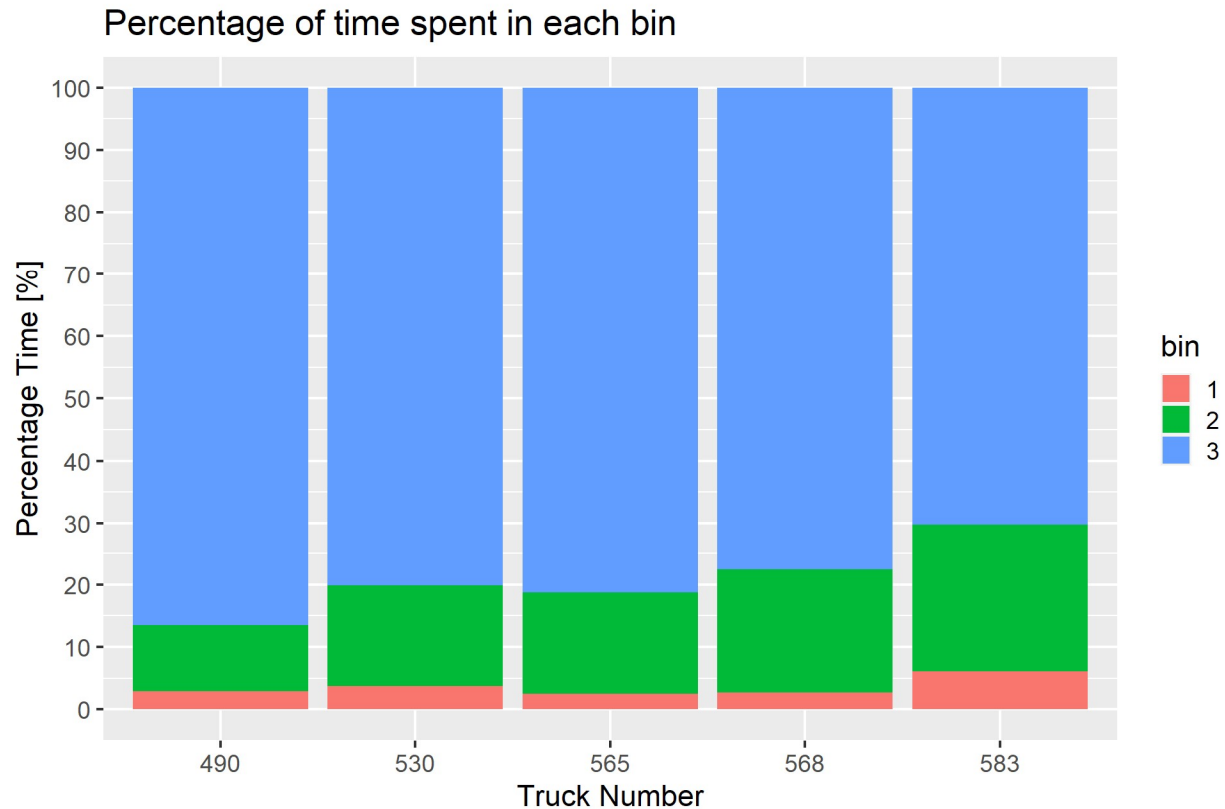
Figure 6: Percentages of Time Spent at Idle (bin 1), Low Load (bin 2), and Medium/High Load (bin 3) Operation for each test truck

Trucks spent between 13 percent on the low end and 30 percent on the high end at idle and low load conditions combined. The time spent at high load ranged from 70 percent on the low end to 87 percent on the high end. Idling time ranged from 2 percent to 6 percent. Trucks with other vocations are likely to exhibit different load profiles in-use. Tractor-trailer trucks, as tested in this study, are members of one of the vocations that exhibits the most consistent uninterrupted high load operation.

An EPA study presented at the 2021 CRC Real World Workshop found that line haul trucks spent 23 percent of their average shift day in city driving, which is similar to the time trucks 530, 565, and 568 spent in their combined idle and low load operation[12]. Truck 490 spent significantly less than this amount of time in idle and low load operation while truck 583 spent more than this amount of time in idle and low load operation.

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[12] Hamady, F. and Duncan, A., "Comparison of Manufacturers In-Use Testing Results Using EPA Not-To-Exceed Test Procedure and EU Moving Averaging Window Method," presented at the 30th CRC Real World Emissions Workshop, March 8 -11, 2021.

Vehicle Emission Results

As described in the Method section, ECCC calculated vehicle NOx and CO_2 emissions for three categories of operation: idle (<6% engine load); low load (6%-20% engine load) and high load (>20% engine load) using the method developed by ARB in its Omnibus regulation.
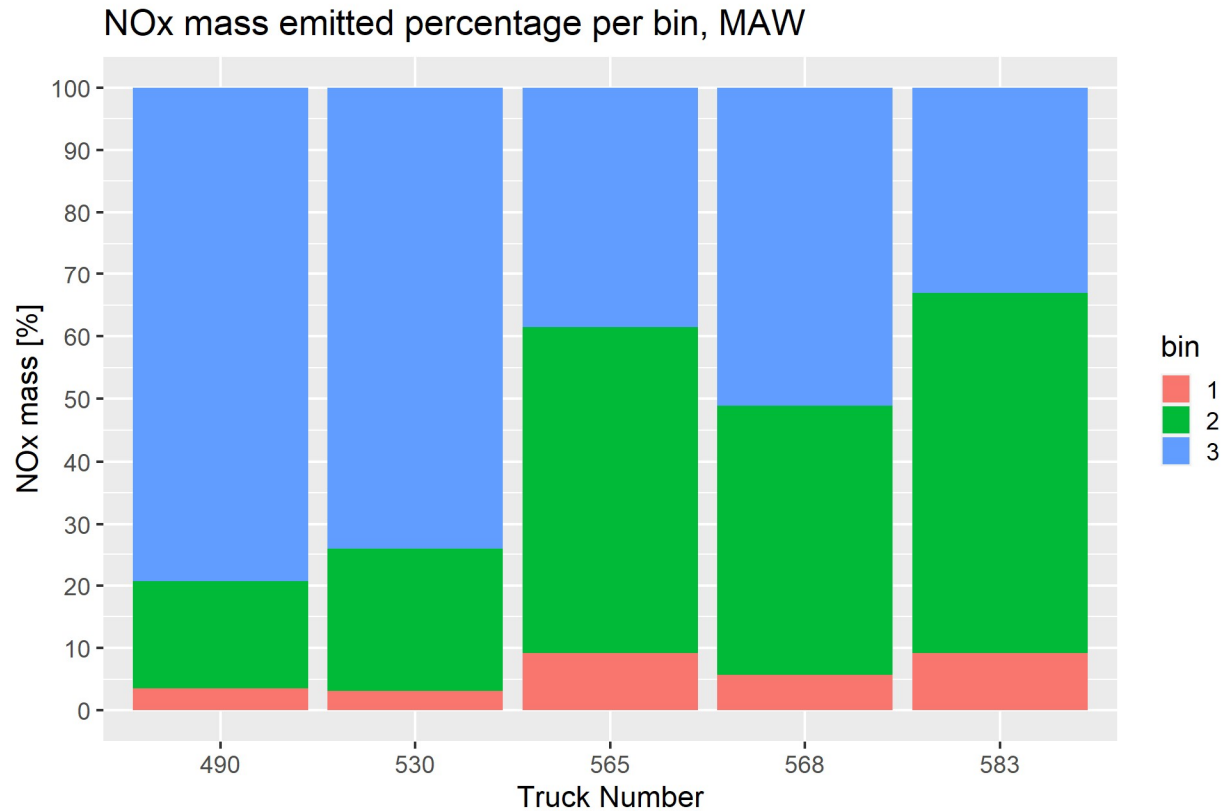
NO$_x$ Emissions

Figure 7: Percentage of NOx Mass Emissions in bins 1, 2, and 3 for Each Truck

Error! Reference source not found. Figure 7 shows the percentage mass of NO$_x$ emitted at idle (bin 1), low load (bin 2), and medium/high load (bin 3) for each of the tested trucks. The percentage mass NO$_x$ emissions in these bins were affected by the percentage of time spent in the different load conditions (shown in Figure 6). For example, truck 490 spent most of its time in medium/high load operation and correspondingly most of the NO$_x$ emitted from this truck was in bin 3, the medium/high load bin. However, the NO$_x$ emission percentages tended to increase in bin 2 when compared to the percentage of time spent in that bin, emphasizing the outsized contribution of low load operation to NO$_x$ emissions. The percentage mass NO$_x$ emitted in bins 1 and 2 combined ranged from a low of 21 percent (in the case of truck 490) to a high of 67 percent (in the case of truck 583).

A Sum-over-sum NOx Emissions, Bin 2, MAW, filled

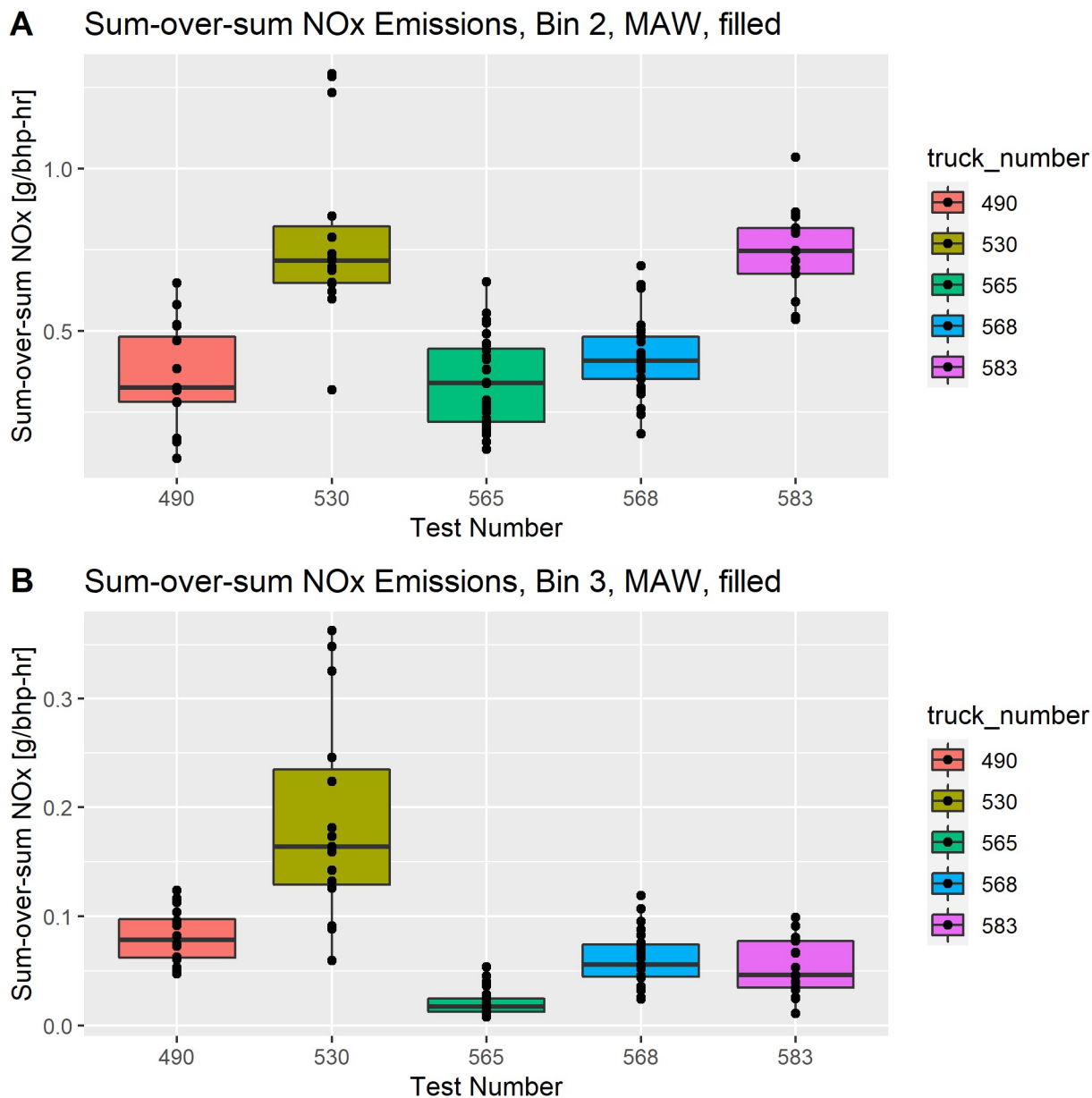**B** Sum-over-sum NOx Emissions, Bin 3, MAW, filled

Figure 8: Sum over Sum NOx Emissions in Low Load and High Load Operation, by Truck

For the sum over sum NOx emissions, Figure 8 shows values for bins 2 and 3 only because these are the two bins that result in g/bhp-hr NOx emissions values like the NTE method. The box plots show the median values as central bars and the box limits denote the locations of the 25th and 75th percentiles of the data. The dots denote the result from each individual test day, showing the spread of values during testing. In the case of low load (bin 2) NOx emissions, a value of 1.0 g/bhp-hr was used to fill times when the NOx sensor was not reporting, as described in the Methods section. The NOx sensor was working and providing data approximately 69 percent of the time in bin 2 and for the remainder of the time, this 1.0 g/bhp-hr value was used. As shown in Figure 8, truck sum over sum NOx emissions in bin 2 ranged from about 0.1 to 1.25 g/bhp-hr on different test days.

Truck 530 had the highest maximum emissions rates of the five trucks with individual sum over sum NO_x emissions rates of up to over 1.25 g/bhp-hr at low load (bin 2) and up to nearly 0.4 g/bhp-hr under high load (bin 3). This truck emitted lower rates of NO_x than these extremes most of the time, with a median NO_x emission rate of 0.75 g/bhp-hr in bin 2 and 0.16 g/bhp-hr in bin 3. Truck 530 is somewhat of an outlier among the trucks with its higher sum-over-sum NO_x emissions. This truck was tested in low temperature conditions, which could have caused additional warm-up time for the selective catalytic reduction (SCR) system and the NO_x sensor. Most trucks emitted very low levels of NO_x, especially during high load operation – frequently reaching levels lower than 0.1 g/bhp-hr in bin 3.

CO_2 Emissions

CO_2 emissions were calculated based on fuel consumption values broadcast by the truck engine control module as described in the Methods section. Figure 9 shows a box plot for each truck's CO_2 emissions, calculated while the trucks operated at low load (bin 2) and medium/high load (bin 3). While there is not a direct relationship between standard test cycles and the in-use cycles driven while fuel consumption data were being logged, the low load and transient cycles observed in bin 2 were more similar to the FTP cycle than the supplemental emissions test (SET) procedure for tractor engines, which has substantial amounts of steady state driving, like in bin 3.
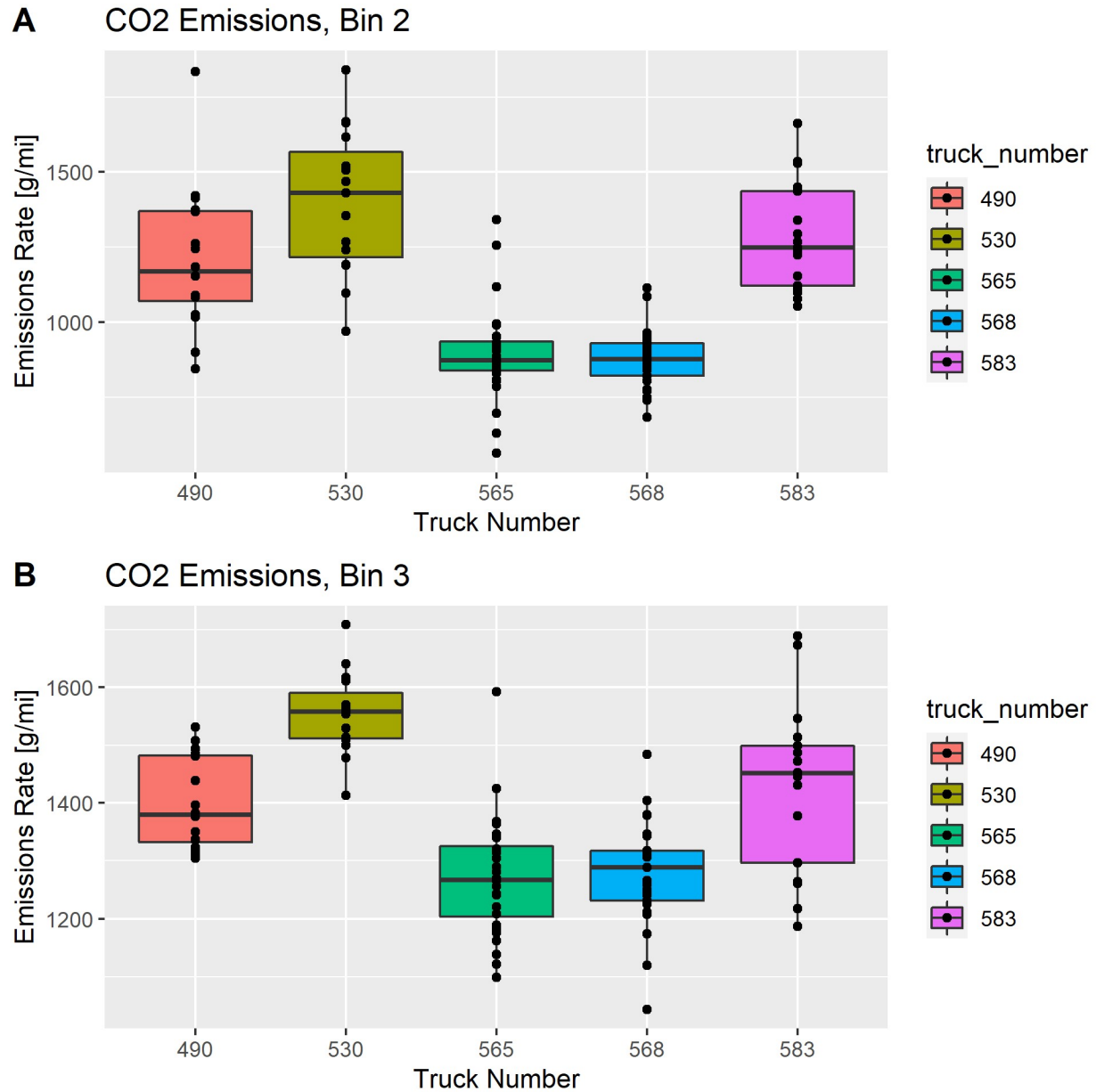
A CO2 Emissions, Bin 2

B CO2 Emissions, Bin 3

Figure 9: Calculated CO$_2$ Emissions for Each Truck at Low Load and Medium/High Load

Trucks operating in colder temperatures (trucks 530 and 583) generally had higher calculated CO$_2$ emissions on a per-mile basis than the trucks operated in warmer conditions in both bins 2 and 3. This could be due to increased road loads at colder temperatures, differences in driving cycle, or differences in composition between summer and winter fuels (which were not accounted for in this analysis). Truck 490 also had slightly higher fuel consumption than trucks 565 and 568, which may be due to driving cycle differences or the fact that it has an older engine model.

Conclusions

The following conclusions can be drawn from this analysis:

- A significant amount of time was spent at low load conditions over the 101 days of data logging. Between 13 percent and 30 percent of the time was spent in the idle and low load bins combined, depending on the individual truck operation.
- A significant percentage of total NO_x over the 101 shifts of data-logging was emitted at idle and low loads (combined). On average, between 21 percent and 67 percent mass of NO_x by vehicle was emitted during these conditions (after additions for times when the NO_x sensor was inactive).
- Only tractor-trailer vehicles were data logged in this study and they spent a majority of their time, between 70 percent and 87 percent, at high load conditions (bin 3). On average, between 33 percent and 79 percent of NO_x was emitted during these high load conditions.
- The ARB MAW approach can be effectively applied to in-use data sets to evaluate and set standards for low load NO_x emissions, however the use of on-board NO_x sensors introduces significant gaps in the sensing data, especially during exhaust system warm-up time.
- Sum-over-sum NO_x emission rates for bins 2 and 3 ranged from below 0.05 g/bhp-hr to over 1.25 g/bhp-hr during the data logging period. For the majority of time that the on-board NOx sensors were operating, trucks emitted NO_x at well below the current 0.2 g/bhp-hr standard to which they were certified.
- NO_x sensors operated 69 percent of the time during bin 2 operation, and 89 percent of the time in bin 3 operation.
- Median VMT of all trucks was 432 miles per day, with individual truck median values varying from 214 to 549 miles per day.

Recommendations

- U.S. federal standards for NO_x during idle and low load operation should be established given the substantial amount of NO_x emissions resulting from low load conditions.
- In addition, a U.S. federal certification test cycle and an in-use test procedure that account for low load and idle NO_x emissions should be established.
- To more accurately measure NO_x emissions in-use using on-board vehicle sensors, new NO_x sensors that can operate at lower exhaust temperatures and during start-up conditions are needed.
- A U.S. federal program to control NO_x should rely on the substantial research and regulatory work ARB has done to put new NO_x standards in place for heavy-duty engines and vehicles.
- More stringent U.S. federal standards for new HD engine and vehicle NO_x emissions should be established.

Appendix A: List of Broadcast Parameters Collected from Data Loggers

Time
Aftertreatment Regeneration Inhibit Switch (bit)
Aftertreatment Regeneration Force Switch (bit)
Actual Retarder - Percent Torque (%)
Drivers Demand Retarder - Percent Torque (%)
Actual Maximum Available Retarder - Percent Torque (%)
Anti-Lock Braking (ABS) Active (bit)
Accelerator Pedal Position 1 (%)
Engine Percent Load At Current Speed (%)
DPF Thermal Management Active (bit)
SCR Thermal Management Active (bit)
Actual Maximum Available Engine - Percent Torque (%)
Engine Torque Mode (bit)
Actual Engine - Percent Torque (Fractional) (%)
Driver's Demand Engine - Percent Torque (%)
Actual Engine - Percent Torque (%)
Engine Speed (rpm)
Engine Demand Percent Torque (%)
Transmission Selected Gear (gear value)
Transmission Actual Gear Ratio (Ratio)
Transmission Current Gear (gear value)
Engine Exhaust Gas Recirculation 1 Mass Flow Rate (kg/h)
Engine Intake Air Mass Flow Rate (kg/h)
Engine Exhaust Gas Recirculation 2 Mass Flow Rate (kg/h)
Engine Exhaust 1 NOx 1 (ppm)
Engine Exhaust 1 Percent Oxygen 1 (%)
Engine Exhaust 1 Gas Sensor 1 Power In Range (bit)
Engine Exhaust 1 NOx 1 Reading Stable (bit)
Engine Exhaust 1 NOx Sensor 1 Preliminary FMI (binary)
Engine Exhaust 1 NOx Sensor 1 Self-diagnosis Status (bit)
Aftertreatment 1 Outlet NOx 1 (ppm)
Aftertreatment 1 Outlet NOx 1 Reading Stable (bit)
Aftertreatment 1 Outlet NOx Sensor 1 Preliminary FMI (binary)
Aftertreatment 1 Diesel Exhaust Fluid Actual Dosing Quantity (g/h)
Aftertreatment 1 SCR System 1 State (bit)
Aftertreatment 1 Diesel Exhaust Fluid Actual Quantity of Integrator (g)
Aftertreatment 1 Diesel Exhaust Fluid Doser 1 Absolute Pressure (kPa)
Aftertreatment 1 Diesel Exhaust Fluid Actual Dosing Quantity (High Range) (g/min)
Certification Engine Family Name (ASCII)
Engine Trip Fuel (High Resolution) (l)
Engine Total Fuel Used (High Resolution) (l)
Aftertreatment 1 Outlet Corrected NOx (ppm)

Engine Exhaust 1 Corrected Nox (ppm)
Aftertreatment 1 Diesel Oxidation Catalyst Intake Temperature (C)
Aftertreatment 1 Diesel Oxidation Catalyst Outlet Temperature (C)
Aftertreatment 1 Diesel Oxidation Catalyst Differential Pressure (kPa)
Aftertreatment 1 Diesel Oxidation Catalyst Intake Temperature Preliminary FMI (binary)
Aftertreatment 1 Diesel Oxidation Catalyst Outlet Temperature Preliminary FMI (binary)
Aftertreatment 1 SCR Intake Temperature (C)
Aftertreatment 1 SCR Outlet Temperature (C)
Engine Coolant Temperature 2 (C)
Aftertreatment 1 Diesel Exhaust Fluid Average Consumption (l/h)
Aftertreatment 1 SCR Commanded Diesel Exhaust Fluid Consumption (l/h)
Aftertreatment 1 SCR Conversion Efficiency (%)
Aftertreatment 1 Diesel Particulate Filter Soot Load Percent (%)
Aftertreatment 1 Diesel Particulate Filter Ash Load Percent (%)
Aftertreatment 1 Diesel Particulate Filter Time Since Last Active Regeneration (s)
Aftertreatment 1 Diesel Particulate Filter Soot Load Regeneration Threshold (%)
Aftertreatment Diesel Particulate Filter Passive Regeneration Status (bit)
Aftertreatment Diesel Particulate Filter Active Regeneration Status (bit)
Aftertreatment Diesel Particulate Filter Status (bit)
Diesel Particulate Filter Active Regeneration Inhibited Due to Low Exhaust Temperature (bit)
Diesel Particulate Filter Active Regeneration Forced Status (bit)
Aftertreatment 1 Diesel Particulate Filter Conditions Not Met for Active Regeneration (bit)
DM28 - Malfunction Indicator Lamp (bit)
DM28 - Suspect Parameter Number (binary)
DM28 - Failure Mode Identifier (binary)
DM28 - Occurrence Count (binary)
DM28 - SPN Conversion Method (bit)
Aftertreatment 1 Total Fuel Used (l)
Aftertreatment 1 Total Regeneration Time (s)
Aftertreatment 1 Total Disabled Time (s)
Aftertreatment 1 Total Number of Active Regenerations (count)
Aftertreatment 1 Diesel Particulate Filter Total Passive Regeneration Time (s)
Aftertreatment 1 Diesel Particulate Filter Total Number of Passive Regenerations (count)
Aftertreatment 1 Diesel Particulate Filter Total Number of Active Regeneration Inhibit Requests (#)
Aftertreatment 1 Diesel Particulate Filter Total Number of Active Regeneration Manual Requests (#)
Aftertreatment 1 Diesel Particulate Filter Average Time Between Active Regenerations (s)
Aftertreatment 1 Diesel Particulate Filter Average Distance Between Active Regenerations (km)
Aftertreatment 1 Diesel Exhaust Fluid Concentration (%)
Aftertreatment 1 Fuel Rate (l/h)
Aftertreatment 1 Regeneration Status (bit)
Aftertreatment 1 Diesel Particulate Filter Intermediate Temperature (C)
Aftertreatment 1 Diesel Particulate Filter Differential Pressure (kPa)
Aftertreatment 1 Diesel Particulate Filter Outlet Temperature (C)
Aftertreatment 1 Exhaust Temperature 1 (C)
Aftertreatment 1 Diesel Particulate Filter Intake Temperature (C)

Engine Fuel Mass Flow Rate (g/s)

Engine Intake Manifold #2 Pressure (kPa)

Engine Intake Manifold #1 Absolute Pressure (kPa)

Engine Exhaust Gas Recirculation 1 Valve 1 Control 1 (%)

Aftertreatment 1 Diesel Exhaust Fluid Tank Volume (%)

Aftertreatment 1 Diesel Exhaust Fluid Tank Temperature 1 (C)

Aftertreatment Diesel Exhaust Fluid Tank Low Level Indicator (bit)

Aftertreatment SCR Operator Inducement Severity (bit)

Aftertreatment 1 Diesel Exhaust Fluid Tank Heater (%)

Engine Intake Manifold 1 Temperature (High Resolution) (C)

Powered Vehicle Weight (kg)

Gross Combination Vehicle Weight (kg)

Engine Exhaust Pressure 1 (kPa)

Instantaneous Estimated Brake Power (kW)

Engine Turbocharger 1 Compressor Intake Pressure (kPa)

Engine Turbocharger 1 Compressor Intake Temperature (C)

Engine Exhaust Gas Recirculation 1 Temperature (C)

Total Vehicle Distance (High Resolution) (m)

Trip Distance (High Resolution) (m)

DM01 - Malfunction Indicator Lamp (bit)

DM01 - Suspect Parameter Number (binary)

DM01 - Failure Mode Identifier (binary)

DM01 - Occurrence Count (binary)

DM01 - SPN Conversion Method (bit)

DM02 - Malfunction Indicator Lamp (bit)

DM02 - Suspect Parameter Number (binary)

DM02 - Failure Mode Identifier (binary)

DM02 - Occurrence Count (binary)

DM02 - SPN Conversion Method (bit)

DM06 - Malfunction Indicator Lamp (bit)

DM06 - Suspect Parameter Number (binary)

DM06 - Failure Mode Identifier (binary)

DM06 - Occurrence Count (binary)

DM06 - SPN Conversion Method (bit)

Engine Total Idle Fuel Used (l)

Engine Total Idle Hours (h)

Engine Turbocharger 1 Speed (rpm)

Nominal Friction - Percent Torque (%)

Engine's Desired Operating Speed (rpm)

Engine's Desired Operating Speed Asymmetry Adjustment (Ratio)

Estimated Engine Parasitic Losses - Percent Torque (%)

Aftertreatment 1 Exhaust Gas Mass Flow Rate (kg/h)

Trip Distance (km)

Total Vehicle Distance (km)

Engine Reference Torque (Nm)

Engine Moment of Inertia (kgm2)
Engine Default Torque Limit (Nm)
Engine Idle Shutdown has Shutdown Engine (bit)
Engine Idle Shutdown Driver Alert Mode (bit)
Engine Idle Shutdown Timer Override (bit)
Engine Idle Shutdown Timer State (bit)
Engine Idle Shutdown Timer Function (bit)
Engine Total Hours of Operation (h)
Engine Total Revolutions (r)
Year (years)
Total Vehicle Hours (h)
Total Power Takeoff Hours (h)
Engine Trip Fuel (l)
Engine Total Fuel Used (l)
Vehicle Identification Number (ASCII)
Engine Coolant Temperature (C)
Engine Fuel 1 Temperature 1 (C)
Engine Oil Temperature 1 (C)
Wheel-Based Vehicle Speed (km/h)
Engine Fuel Rate (l/h)
Engine Instantaneous Fuel Economy (km/L)
Engine Average Fuel Economy (km/L)
Engine Throttle Valve 1 Position 1 (%)
Barometric Pressure (kPa)
Cab Interior Temperature (C)
Ambient Air Temperature (C)
Engine Intake Manifold #1 Pressure (kPa)
Engine Intake Manifold 1 Temperature (C)
Engine Intake Air Pressure (kPa)
Engine Exhaust Temperature (C)
Alternator Current (A)
Charging System Potential (Voltage) (V)
Battery Potential / Power Input 1 (V)
Fuel Level 1 (%)
Latitude
Longitude
Altitude
Velocity
Heading
Date
Time
FixType
NumSats
DOP